Power Control and Energy Management Strategies for Large-scale PV and Battery Energy Storage Hybrid Generation Systems

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Abstract—**After introduce the structure of the PV and battery energy storage system (BESS) hybrid system (PV-BESS), a novel control strategy on the basis of different scenarios has been proposed, so as to track the demand power while trying to increase utility of solar power as much as possible. To evaluate the control method, its performance in a practical PV-BESS project in Qinghai has been demonstrated. Two cases have been used to illustrate how the BESSs operate to help PV generation track the demand power under the control strategies. The effectiveness of the proposed methods was verified by practical operation and it was illustrated that although the different characteristics of the PV generation in the two cases caused BESS response differently, they both have good performance in demand tracking.**

***Index Terms*—Battery Energy Storage Station, PV Power Station, Power Demand Tracking, Battery Energy Management**

I. Introduction

The serious pollution and greenhouse gas emission problem caused by fossil fuels encourages the development of renewable generation technology, one of which is the rapidly increased photovoltaic generation [1]-[3]. Chinese PV installation capacity went up to the largest around the world with the accumulated around 61GW by June 2016[4],[8]. However, solar energy source is intermittent and variable in nature, characterized as fluctuation. The fluctuation could affect the stability and reliability of power grid and also may lead to the possible solar power curtailment. Therefore, reducing power fluctuation of PV power will benefit to the safety and economy of power grid operation [5]-[7].

Now the major challenges of large-scale PV generation are: 1) The cloud shadowing can cause drastic fluctuation of PV generation, which will affect safety and stability of power grid; 2) The intermittent and uncertain characteristics of PV power result into pressures on power grid frequency regulation and peak load shifting; 3) The regional limitation on PV generation integration leads to solar power curtailment, which affect the capacity of PV generation. As the increasing of large-scale PV generation integrating into power system, the peak load shifting insufficiency problem of the regional grid will become more significant and become the barrier for PV generation consumption. The transmission and consumption of large-scale PV generation has been an emergent issue now. There should be a more flexible method to deal with the challenge caused by fast developing PV generation. Large-scale energy storage station provides a flexible and reliable regulating resource. It can restrain the intermittency and uncertainty of PV generation, improving peak load shifting ability of power grid.

As controllable devices, the battery energy storage system (BESS) can flexibly adjust charging or discharging power according to the demand. Since BESS allowing to restore an adequate level of controllability, it can be used to mitigating the PV power fluctuation [8]-[9].

There has been widely research on using energy storage system to address solar power fluctuation from difference perspectives. Considering the SOC of BESS and mitigating result, [10] uses filter to form power object and make real-time regulation, having a good performance in reducing power fluctuation. [11] deals with the hybrid energy storage problem and adopts wavelet packet-fuzzy control, which is proved to be better than the low-filter control. According to feedback of battery SOC, [12] use slope control strategy to mitigate the fluctuation of wind-solar power generation. The short-term prediction technology is used in [13] to optimize BESS power and it increase the system's capacity in tracking schedule generation. [14] apply the wavelet filter in the battery energy storage station to smooth power fluctuation of the wind/PV hybrid power system. [15] and [16] focus on the control strategies for battery units, the former proposed the strategies for autonomous Control of PV and battery Units in islanded Microgrids while the latter described a new configuration of the three-level inverter implementing in the advance control strategy.

In China, there are a number of large-scale BESS demonstration projects currently underway. For example, in Zhangbei, a large-scale BESS, which includes a 14 MW/63 MWh lithium-ion BESS and a 2 MW/8 MWh vanadium redox

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flow BESS, has been put into operation. It is part of a national wind, PV, storage and transmission demonstration project. The purpose of this project is to smooth the wind and PV power fluctuations and trace the scheduled power outputs to grid. Further, Guodian LongyuanWoniushi wind farm energy storage power station, using total vanadium flow batteries (5 MW/10 MWh), is adopted mainly to resolve wind-curtailment and brownout issues arising at the Woniushi wind farm. The BESS of Southern Power Grid Shenzhen Baoqing adopted the lithiumion battery (planned capacity is 10 MW and completed capacity is 4 MW/16 MWh) to achieve peak load shaving, frequency regulation, and voltage regulation, etc.

Large-scale battery energy storage system can improve PV generation capacity, increasing PV generation utility rate. This paper proposes a coordinated control and energy management strategies for the PV and BESS (PV-BESS) hybrid system. The control method adjusts itself according to different scenarios so as to track the power demand while trying to increase solar power generation. To evaluate the control method, we demonstrate its performance in the practical PV-BESS project. The control method through optimizing the PV-BESS power generation to improve the PV power uncertainty and increase the PV generation capacity, thus help promote the power grid and PV-BESS system to operate efficiently and economically.

This paper is organized as follows. Section II presents the structure of PV-BESS system. Section III describes the proposed control strategy of PV-BESS generation system. Performance demonstrations of the control method are presented in section IV. Section V is the conclusion.

II. Structure of PV-BESS System

We implement the designed control method in a practical PV-BESS station in Qinghai. The solar station has the installed max power capacity of 53.5 MW. It includes 50 centralized solar cells with power capacity of 1 MW, which connecting to the 35kV bus line through inverters. The battery energy storage station has the total installed capacity of 15MW/18MWh. It consists of 5 storage units with capacity of 3MW/3.6MWh. Each storage unit is equipped with control and monitoring system (CMS) and 6 power converter systems (PCS), which are connected to the lower voltage side of the transformer. The system structure is illustrated in Fig.1 and the topology for sub-BESS under transformer unit is shown as Fig.2.

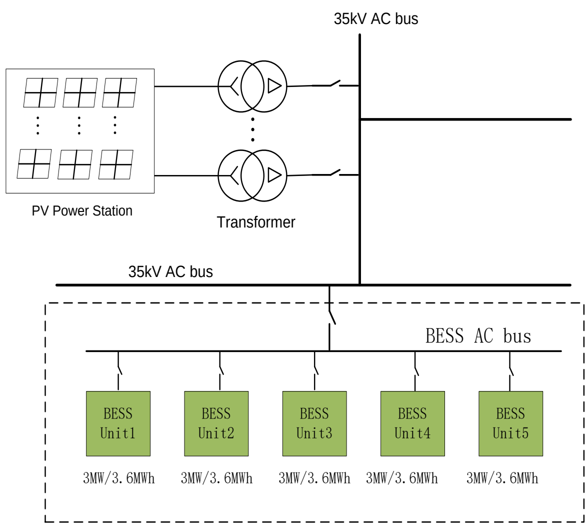


Fig. 1 PV-BESS hybrid system structure

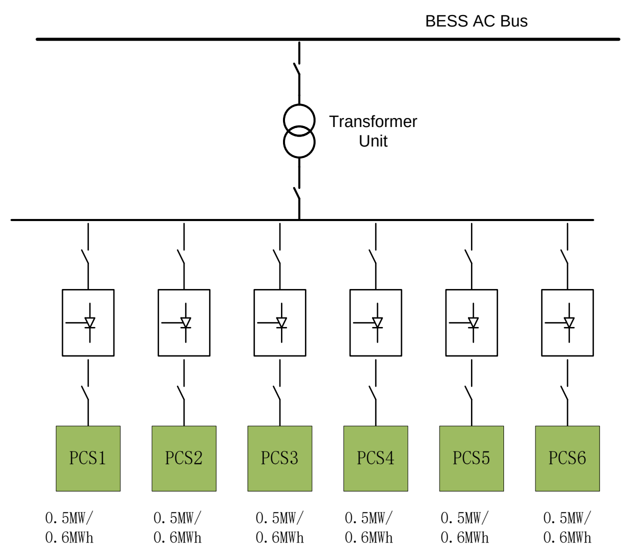


Fig. 2 Topology for sub-BESS under transformer unit

III. Power Control and Battery Energy Management Strategy of PV-BESS Generation

This paper proposed a coordination control strategy. First the PV generation schedule should be pre-processed before sent to the PV modules, then the PV modules will send back the value of PV power to BESS to determine the BESS output value.

A. Pre-processing

This paper defines $\gamma(\gamma>0)$ as the power deviation. γ pluses PV-BESS power output schedule value $P_{plan}(t)$, which is sent from upper generation dispatching center at time *t*, is to determine the objective value of PV station output power $P_{goal}(t)$ at time *t*. The equation is shown as following:

$$P_{goal}(t) = \max\left(P_{plan}(t), P_{PV}(t-\Delta t)\right) + \gamma \qquad (1)$$

where $P_{PV}(t-\Delta t)$ is the output power of PV station at time (t-Δt); Δt is the time interval of the PV-BESS generation control strategy.

B. Control Strategy

1) Constraint of Battery Storage Station

The BESS power value should be positive under discharging condition and negative under charging condition. Thus, the constraint should be:

$$SOC_{low} \leq \mathrm{SOC}(t) \leq SOC_{high} \qquad (2)$$

$$SOC(t)P_{chmax} \leq P_{BESS}(t) \leq \mathrm{SOC}(t)P_{dischmax} \qquad (3)$$

where SOC_{low}, $\mathrm{SOC}(t)$, SOC_{high} respectively are SOC lower bound, SOC value at time t, and SOC upper bound; P_{chmax} is the largest charging rate, negative value; $P_{dischmax}$ is the largest discharging rate, positive value; $P_{BESS}(t)$ is the BESS output power at time t.

2) Control Objective

The control objectives are described as follows:

$$P_{BESS}(t) + P_{PV}(t) \leq P_{plan}(t) \quad (4)$$

$$P_{BESS}(t) + P_{PV}(t) \approx P_{plan}(t) \quad (5)$$

where $P_{PV}(t)$ is the feedback PV power of PV modules at time t.

3) Method of Determining BESS Power

As shown in Fig. 3, according to the multiple logical judgement of the power information of PV station, BESS and PV-BESS, there are different scenarios corresponding to different power output. The specific method is shown as following:

Scenario 1: when $P_{plan}(t) \geq P_{PV}(t)$ and in the PV-BESS system, PV station output power stay as current value $P_{PV}(t)$.

If the SOC of BESS reached the SOC lowest bound, the BESS power output would be 0, that is $P_{BESS}(t) = 0$; if the SOC of BESS higher than the SOC lowest bound, then output power of BESS is determined by the power objective function—the maximum power output:

If $P_{dislimit}(t) + P_{PV}(t) \geq P_{plan}(t)$, then

$$P_{BESS}(t) = P_{plan}(t) - P_{PV}(t) \quad (6)$$

If $P_{dislimit}(t) + P_{PV}(t) < P_{plan}(t)$, then

$$P_{BESS}(t) = P_{dislimit}(t) \quad (7)$$

Scenario 2: when $P_{plan}(t) < P_{PV}(t)$, the PV power may change depends on different conditions.

If the SOC of BESS reached the SOC highest bound, the BESS power output would be 0, that is $P_{BESS}(t) = 0$, and the PV output power remains as $P_{PV}(t)$; if the SOC of BESS lower than the SOC highest bound, then output power of BESS is determined by the power objective function—the maximum power input:

If $P_{PV}(t) - |P_{chlimit}(t)| < P_{plan}(t)$, the PV station output power order stay the same as current value $P_{PV}(t)$. $P_{chlimit}(t)$ is the charging limit. Apart from the output power to power grid, the surplus PV power will be used to charge BESS batteries. The output power order of BESS is;

$$P_{BESS}(t) = P_{plan}(t) - P_{PV}(t) \quad (8)$$

If $P_{PV}(t) - |P_{chlimit}(t)| \geq P_{plan}(t)$, then make solar power curtailment. The output power order of BESS and PV station are:

$$P_{BESS}(t) = P_{chlimit}(t) \quad (9)$$

$$P_{PV}(t) = P_{plan}(t) - P_{BESS}(t) \quad (10)$$

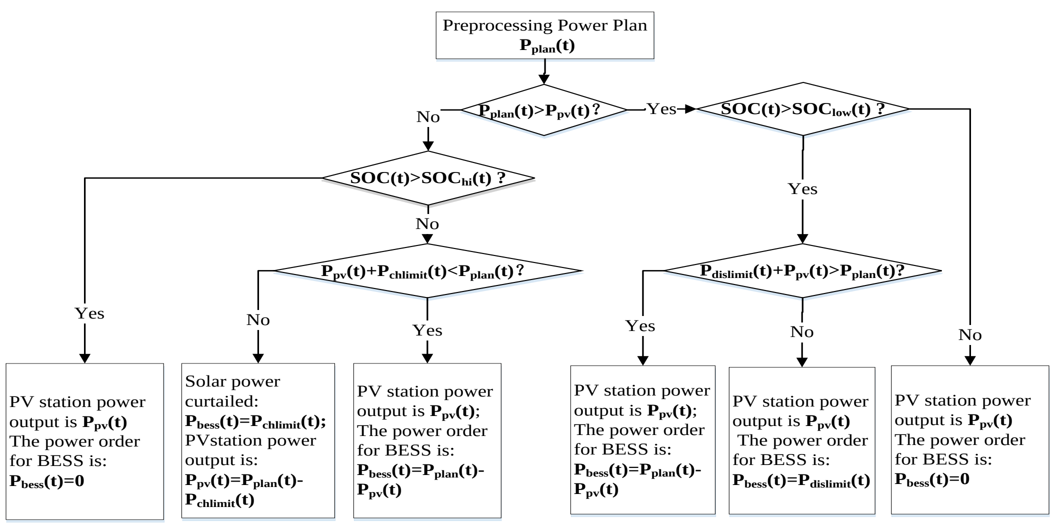


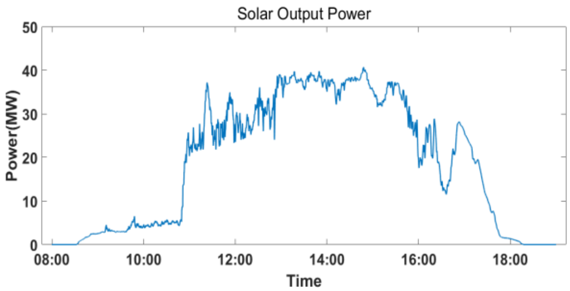
Fig. 3 Power control and battery energy management flow chart of PV-BESS systems

IV. PERFORMANCE EVALUATION

The performance evaluation of the control method is carried out by using the case study. As illustrated in section II, the PV-BESS hybrid power system which our proposed method is implemented to has the PV generation with installed rated power capacity of 50 MW and BESS with installed capacity of 15MW/18MWh. The BESS consists of 5 transformer units, each of which has 6 paralleled PCSs with capacity of 3MW/3.6MWh

The PV generation is not just intermittent and uncertain within one day, but also varying among days with different weather conditions. Sunny days have much more available solar power than cloudy days. The BESS power limits and SOC bounds can lead to PV power curtailment. This paper chooses two typical days (case I and case II) to represent them respectively and to evaluate the performance of our designed control method under different weather conditions. In the pre-processing part of our control strategy, the parameter power deviation γ we use is 5% of the PV station rated power, which equals to 2.5MW.

Fig. 4 is the solar power output of the case I and case II. It shows that the two days represent solar power generation with different weather conditions. Case I represents a sunny day while case II has the feature of a cloudy day. Fig. 5 shows the solar power boxplot of case I and case II. The case I has higher average value and more points locate inside the box (from 25 percentile to 75 percentile), which means more concentrated around the median value.



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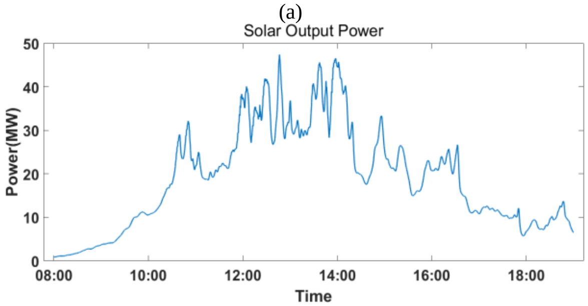

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Fig. 4 PV station power output (a) case I (b) case II

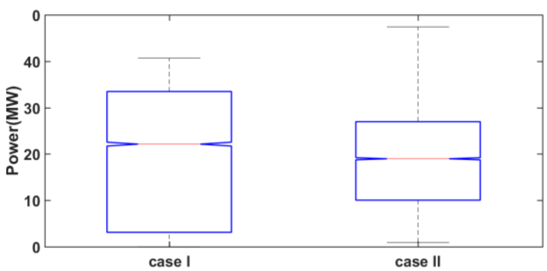
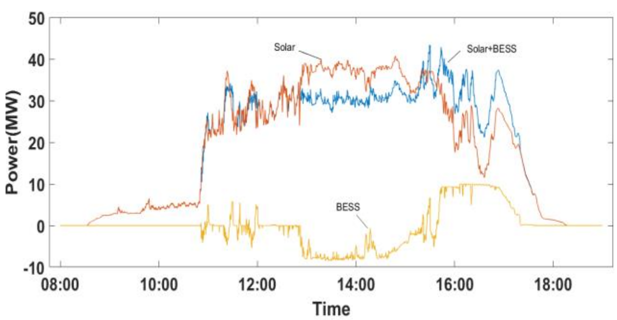


Fig. 5 Boxplot of PV station power output



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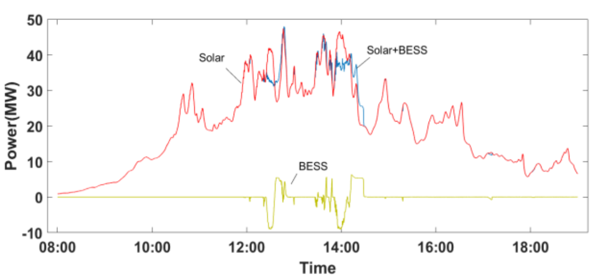

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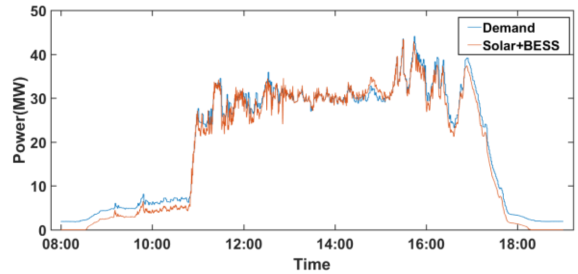
Fig. 6 Power profiles of PV, BESS and PV-BESS (a) case I (b) case II

Fig.6 and Fig. 7 are the power profile of PV-BESS and PV-BESS Power Tracking Demand Power. The graphs illustrate how the BESS works to make the total power meet the requirement of power demand.



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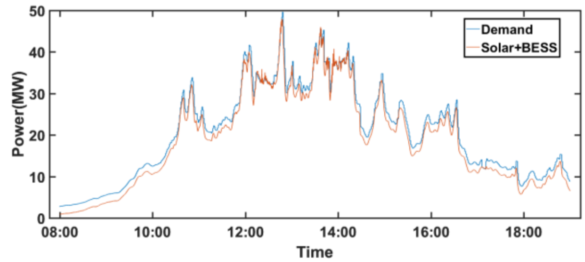

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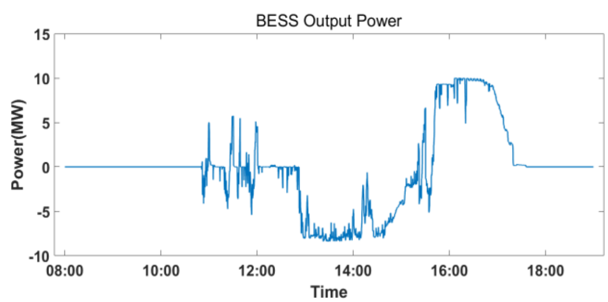
Fig. 7 Power profiles of PV, BESS and PV-BESS (a) case I (b) case II

Table I show the performances of PV-BESS power tracking demand power in the two cases. They illustrate that the PV-BESS output power track the demand power closely. As shown Table I, both cases have good performance in tracking demand power. Both have low rate of PV-BESS power higher than demand power. In the situation that PV-BESS is power higher than demand power, the differences hardly over 10 percent of demand power. This indicates that both case I and case II are tracking the demand power very well. It seems that out that case II has even better performance than case I, which can be explained by the BESS power profiles and SOC profiles shown in Fig. 8 and Fig. 9.



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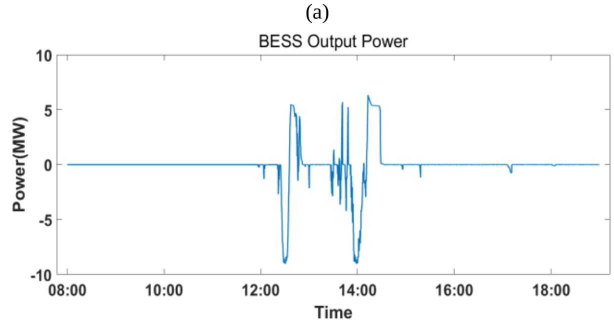

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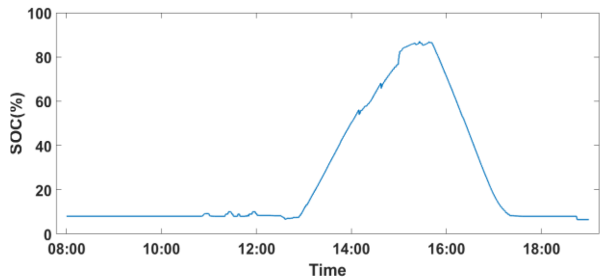
Fig.8 BESS power output (a) case I (b) case II

TABLE I

PERFORMANCE OF PV-BESS POWER TRACKING DEMAND POWER.

$\Delta P = P_{plan} - (P_{PV} + P_{BESS})$	Percentage	
	Case I	Case II
$\Delta P > 0$	78%	93%
$-0.1P_{plan} < \Delta P < 0$	22%	7%
$-0.1\,P_{plan} > \Delta P$	0%	0%



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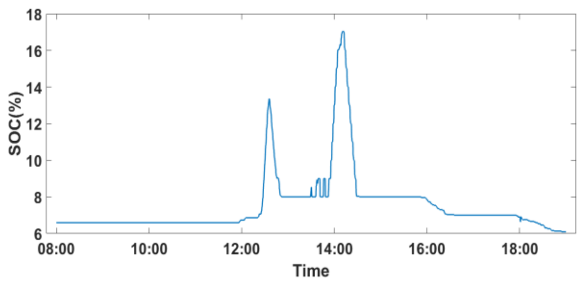
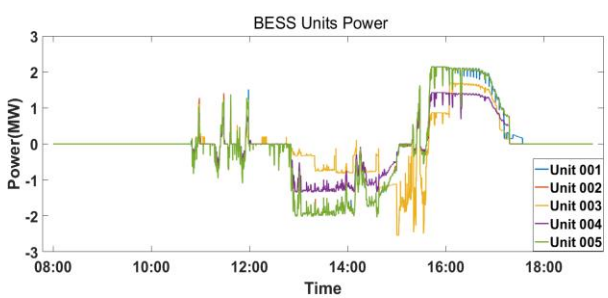


(b)

Fig.9 The curve of BESS SOC (a) case I (b) case II

It appears that BESS in case I works more frequently than in case II, which means case I requires more participation of BESS to help PV-BESS power output track the demand power. The SOC profiles of case I and case II are different in their range. SOC of case I ranges from 10% to 90%, while the largest SOC value of case II is no more than 20%. The SOC limit causes the BESS charging power limit, and that explains why there are slightly higher rate of power overflow in case I than in case II.



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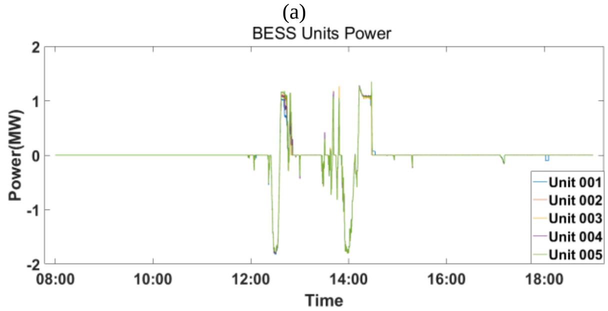
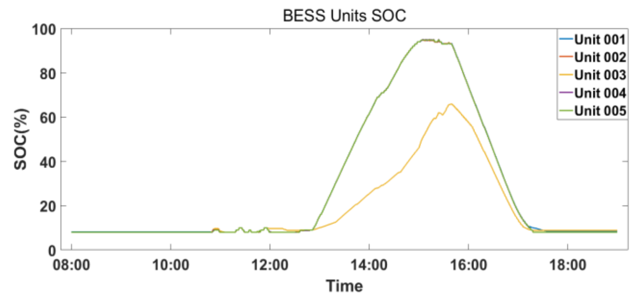


(b)

Fig.10 Power profile of each transformer unit (a) case I (b) case II

Figs. 10 and 11 respectively are power profile and SOC profile of each transformer unit. They illustrate the work difference ad trend similarity among the five units. In Fig. 11 the SOC profile of transformer unit 3# in appears quite different from the others. It is because of parts of the power converter systems are under reservation which affect the charging power of this unit.

To illustrate how the PCSs in the transformer unit of the battery storage station work uniformly, we present the power and SOC profiles of transformer unit #2. As shown in Fig. 12 and Fig. 13, we can find that the power and SOC curves of PCS1-PCS6 demonstrate all the PCSs working uniformly.



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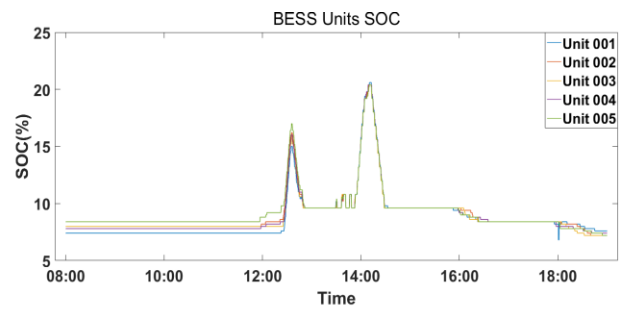

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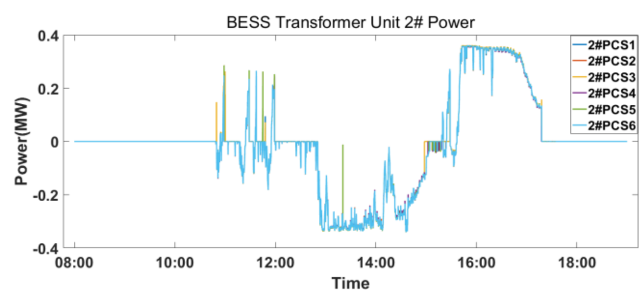
Fig.11 SOC profile of each transformer unit (a) case I (b) case II



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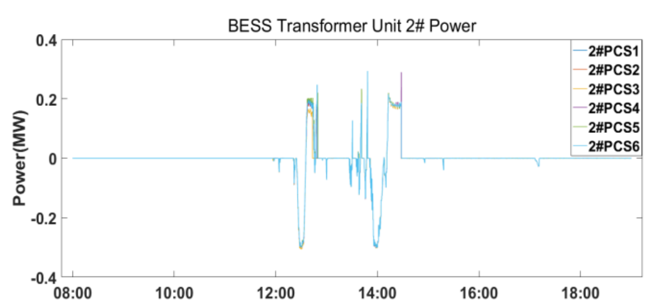

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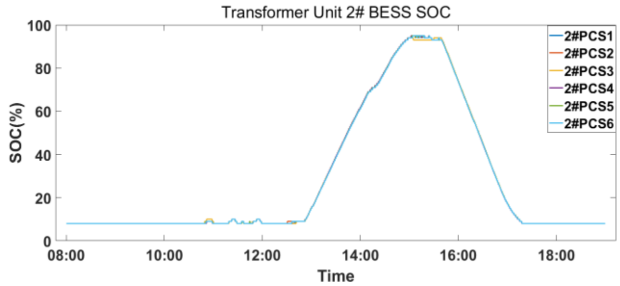
Fig.12 Power of each PCS unit of transformer unit #2 (a) case I (b) case II



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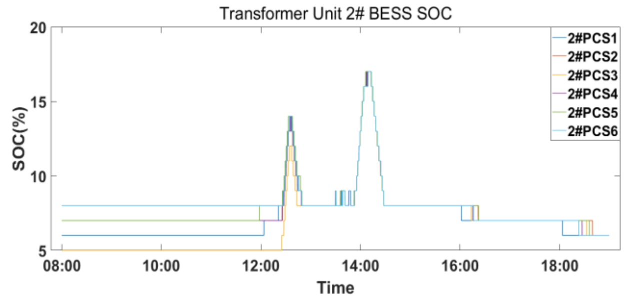

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Fig.13 SOC of each PCS unit of transformer unit #2 (a) case I (b) case II

V. Conclusion

This paper proposes a coordinated control and energy management strategy for the PV-BESS system. The pre-processing is firstly made for PV generation schedule before sent to the PV modules. Then the BESS output power can be determined through the PV power value sent back by PV modules. The control method aims at regulate the PV-BESS hybrid power match with the demand power and adopts variant strategies according to different scenarios. Then we demonstrated its performance in a practical PV-BESS project.

This paper illustrated the effect of solar power feature on the BESS and demonstrated a satisfying performance on tracking demand power. The operation results of different cases obtained from practical PV-BESS project demonstrate that the proposed power control strategy can track demand power effectively. Under both of the typical weather conditions, implementing our control strategy can have a good tracking performance, as well as manage the BESS power and SOC within a specified target region. However, the objective of this paper only considers demand power tracking. The economy effect of solar power curtailment will be discussed in the near future combined with the BESS service life optimization.

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